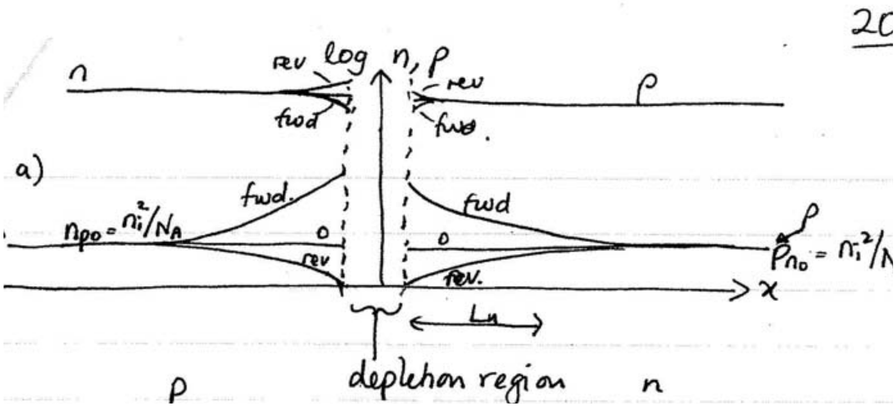
3.15 - Problem Set 3 Solutions

Problem 1

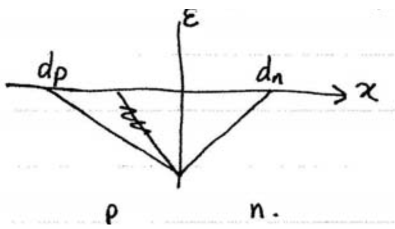
a.

Forward Bias: e^- injected into p side, leads to high e concentration near



depletion region, decays away with characteristic length L_n (10s of μm) slight reduction of electron concentrtion near depletion region of n side.
Reverse Bias: e collected from p side, pins $n = 0$. (Very slight increase in n on the n side.)

b.
Breakdown: ϵ in depletion region $= 10^5$V/cm.
Assume depletion approximation: if $N_D = N_A$, $d_n = d_p$.



$$\text{Max } \epsilon = \frac{N_A e d_p}{E_D E_R} \text{ or } \frac{N_D e d_n}{E_D E_R}$$

$$\text{We know: } d_n = \left(\frac{2E_D E_R V_0}{e} \frac{N_A}{N_D(N_A + N_D)}\right)^{\frac{1}{2}}$$

and

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0258\ln\left(\frac{10^{15}\cdot 10^{15}}{10^{20}}\right.$$

So:

$$\begin{aligned} d_n &= \left(\frac{2\times 1.05\cdot 10^{-12}\times 0.59}{1.6\cdot 10^{-19}} \times \frac{10^{15}}{10^{15}(2.5\times 10^{15})}\right)^{\frac{1}{2}} \\ &= 6.2\times 10^{-5}\text{cm or } 0.6\mu\text{m} \end{aligned}$$

Therefore:

$$\epsilon = \frac{N_D e d_n}{E_D E_r} = \frac{10^{15}\times 1.6\cdot 10^{-19}\times 6\cdot 10^{-5}}{1.05\cdot 10^{-12}} = 0.9\cdot 10^4\text{V/cm}$$

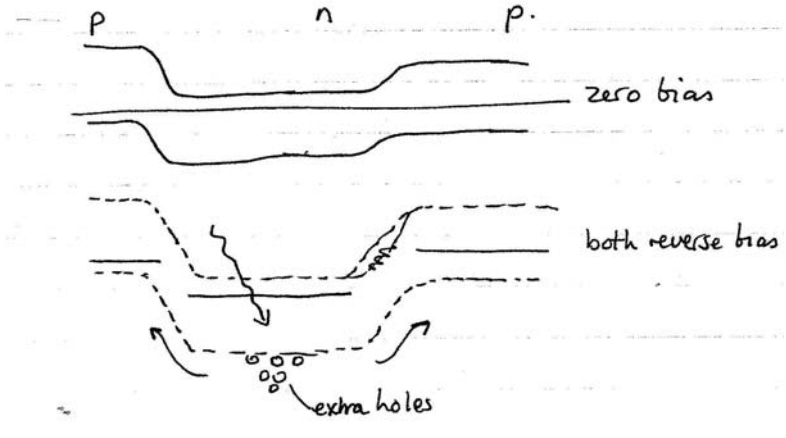
For breakdown, applying voltage V_A extends the depletion region, and raises ϵ.
d_n increases by a factor of $\sqrt{\frac{V_0+V_A}{V}}$ and so does ϵ.
If avalanche occurs at 10^5 V/cm:

$$\frac{10^5}{0.9\times 10^4} = \sqrt{\frac{V_0+V_A}{V_0}}$$
$$V_0 + V_A = 72.8\text{V}$$

So reverse bias of ≈72V is needed for breakdown.

c.

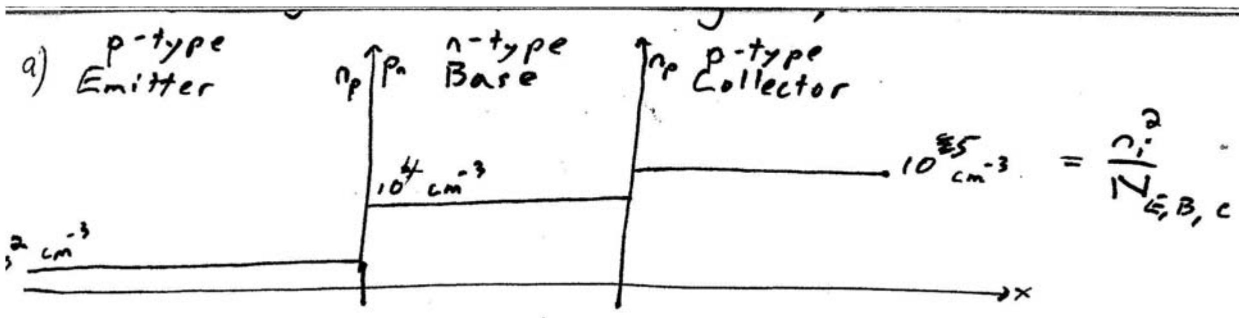
We collect carriers in reverse bias pn jn so we might bias both jns in reverse. Then any holes produced in base will go across either EB or BC jn, depending on which direction they go. A large hole current flows into E and C from B. Electrons flow out of the base contact. $I_B \propto$ light intensity. (In fact it would work even without bias.)



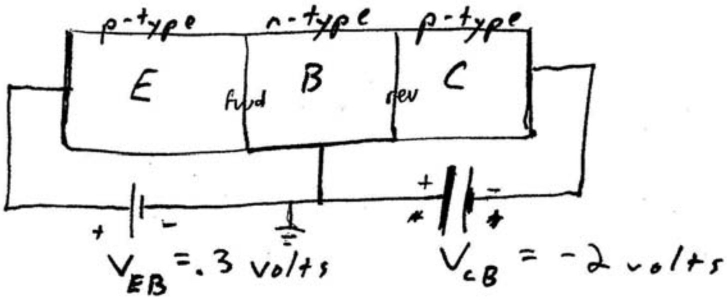
Note: Putting EB in fwd bias means a large current already flows through E→C, so the light-generated carriers would not add much to this.

Problem 2

a.

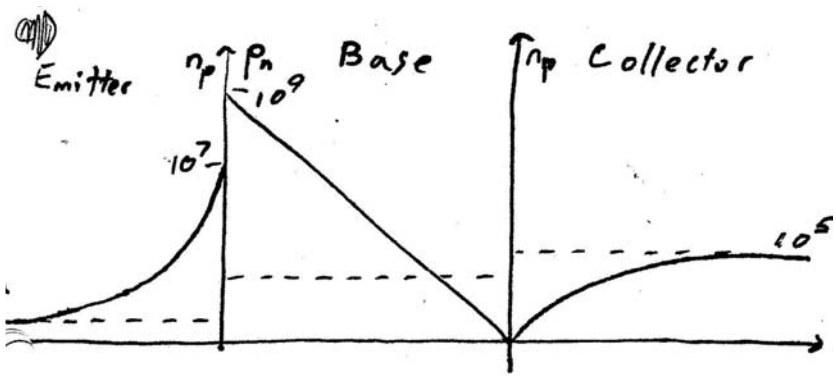


b.



The E-B junction is forward-biased.
The C-B junction is reverse-biased.
⇒ We are in the forward-active regime. $I_E \approx I_C >> I_B$.

c.



$$n_p = n_i^2 \exp(aV_A/kT)$$

At E-B depl. region edges:

$$\begin{aligned} n_p(0) &= \frac{n_i^2}{10^{18}} \exp q_0^3 kT \\ &= 10^9 \text{cm}^{-3} e^- inemitter \end{aligned}$$

$$\begin{aligned} p_n(0) &= 10^4 \exp q_0^3 kT \\ &= 10^9 \text{cm}^{-3} h^+ inbase \end{aligned}$$

d.

To be consistent with nomenclature, we should refer to this current density at J_{CE}. We have diffusion current in the base, from the emitter to the collector.

$N_{D,B} = 10^{16}\text{cm}^{-3} \Rightarrow \mu_p = 440; D_p = \mu\frac{kT}{q} = 11.4\frac{\text{cm}^2}{\text{sec}}$.

$$J_{CE} = -qD_p\frac{dp}{dx} = -1.6 \cdot 10^{-19} \cdot 11.4\frac{10^9}{5 \cdot 10^{-4}} = -3.65\frac{\mu A}{\text{cm}^2}$$

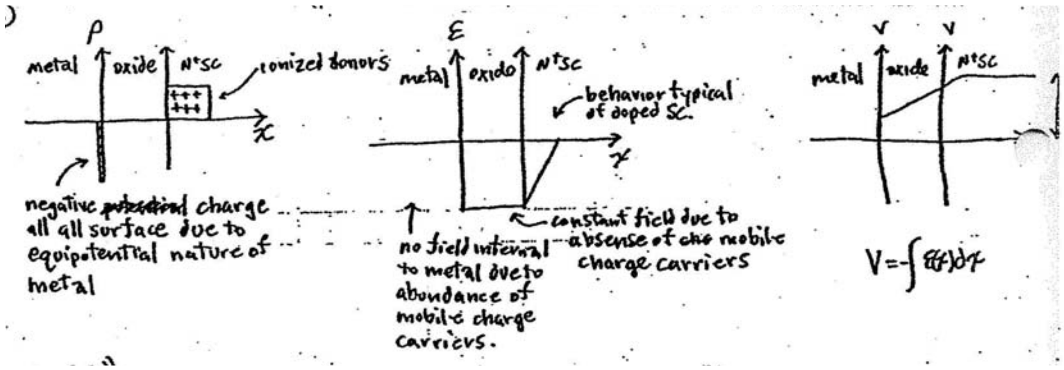
Note: holes flow from emitter to collector, so collector-to-emitter current is negative.

e.

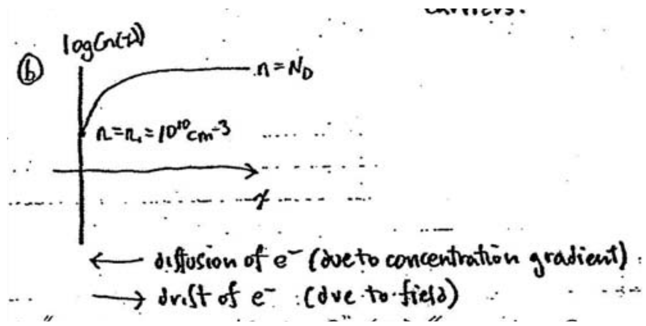
This would reverse-bias the E-B junction putting the device in the cut-offf regime, and causing I_{CE} (J_{CE}) to cut-off (go to ≈ 0).

Prolbem 3

a.



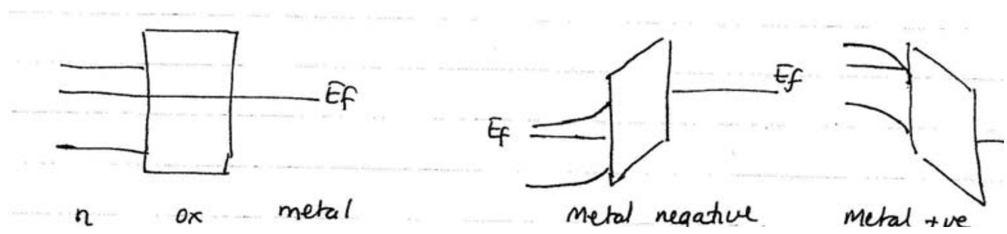
b.



"Is x in equilibrium?" ⇔ "Is the fermi level flat within x?" Within the semiconductor the Fermi Level remains flat, meaning there is no tendency for charge to flow in either direction. The semiconductor, considered separately from the rest of the system is "in equilibrium" within itself. The additional band bending due to the applied MOS voltage is then considered to create a sort of new built-in voltage, similar to what we saw in a pn junction.

Problem 4

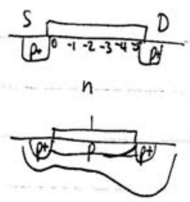
a.



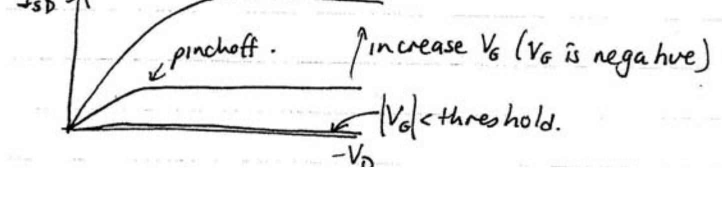
Material masked in black is oxide (SiO_2)
V_G negative: initially electrons depleted from S/C, eventually goes into inversion (becomes p type). Metal gate has depletion of electrons close to interface.
V_G positive: electrons accumulate in S/C and also in metal near interface.

b.

Zero V_g:



pn junction at D is in large reverse bias, no current flows S-D.
Negative V_g:

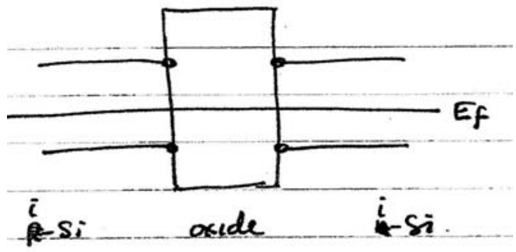


At threshold V_g, n goes into inversion and forms channel. Curren I_{SD} flows, but channel is narrower near D, and eventually pinches off → limits I_{SD}.

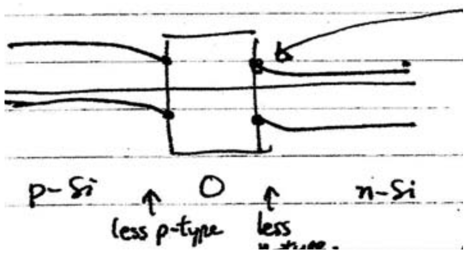
Positive V_G: No channel forms, no conduction from S to D.

Problem 5

a.



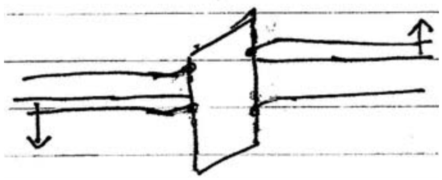
Equilibrium undoped - Ideal.



Like MOS¡ the S/C - oxide band offsets are fixed, same for all doping levels.
Equilibrium - Band bending casuses depletion near each interface.

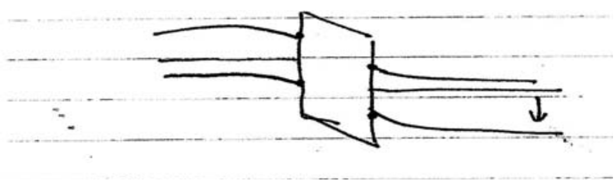
b.

Bias 'forward' → p side positive.



This 'unbends' the bands near the interface. Each side has less depletion than the unbiased case. A large bias could lead even to accumulation. Acts like a capacitor.

Bias 'reverse'



This is where depletion increases - we can eventually get inversion.

No current flows in any of these since oxide doesn't conduct.